

Purdue University

Purdue e-Pubs

International Refrigeration and Air Conditioning
Conference

School of Mechanical Engineering

2021

Low Melting Temperature Brazing Materials for Aluminum Heat Exchanger Fabrication

Hui Zhao

University of Illinois at Urbana-Champaign, huizhao@illinois.edu

Stefan Elbel

University of Illinois at Urbana-Champaign

Pega Hrnjak

University of Illinois at Urbana-Champaign

Follow this and additional works at: <https://docs.lib.purdue.edu/iracc>

Zhao, Hui; Elbel, Stefan; and Hrnjak, Pega, "Low Melting Temperature Brazing Materials for Aluminum Heat Exchanger Fabrication" (2021). *International Refrigeration and Air Conditioning Conference*. Paper 2188.

<https://docs.lib.purdue.edu/iracc/2188>

This document has been made available through Purdue e-Pubs, a service of the Purdue University Libraries.

Please contact epubs@purdue.edu for additional information.

Complete proceedings may be acquired in print and on CD-ROM directly from the Ray W. Herrick Laboratories at

<https://engineering.purdue.edu/Herrick/Events/orderlit.html>

Low Melting Temperature Brazing Materials for Aluminum Heat Exchanger Fabrication

Hui ZHAO^(1,2,*), Stefan ELBEL^(1,2), Pega HRNJAK^(1,2)

¹University of Illinois at Urbana-Champaign
Department of Mechanical Science and Engineering
1206 West Green Street, Urbana, IL 61801, USA

²Creative Thermal Solutions, Inc.
2209 North Willow Road, Urbana, IL 61802, USA

* Corresponding Author Email: huizhao@illinois.edu

ABSTRACT

The manufacturing of compact aluminum heat exchangers, such as microchannel heat exchangers, involves the controlled atmosphere brazing process. The joining of different parts, e.g., tube to header, tube to fin, is accomplished by molten brazing filler metal with the assistance of fluxes. The most commonly used brazing materials for aluminum heat exchangers are Al-Si alloys which offer many advantages, such as excellent wettability and material compatibility with the base materials. However, some limitations of the traditional Al-Si filler metals also exist: (1) very precise control of the brazing temperature is critical because of the small difference between the melting temperatures of the filler and base metals; (2) the choices of the base metals are limited to certain alloys such as the 3xxx and 1xxx aluminum alloys due to the material compatibility issues. The Zn-Al filler metals have relatively low melting temperatures (<500 °C) compared to the Al-Si filler metals (> 575 °C). In this paper, experimental brazing trials of header to the extruded aluminum tube using Zn-Al filler metal at a relatively low brazing temperature range (< 550 °C) are performed. Various base materials are selected for wettability study. The baseline tests using the traditional Al-Si filler metal are also performed for comparison purposes. Corrosion tests and metallurgical analysis are performed on the post-brazing assemblies. The experimental results show good joint integrity using Zn-Al filler metal but inferior corrosion resistance. The significantly lower brazing temperature not only offers a potentially lower cost of the manufacturing process (less energy consumption) than the traditional CAB process, but also reduces the risk of manufacturing defects due to overheating. However, the long term heat exchanger reliability, such as the corrosion resistance and mechanical durability using the Zn based filler metal remains to be investigated and explored.

Keywords: Aluminum heat exchanger, low-temperature brazing.

1. INTRODUCTION

The manufacturing of compact aluminum heat exchangers relies on the brazing process to join different components by applying brazing filler metal at the joint location. The commonly used brazing materials for aluminum heat exchangers are Al-Si alloys which provide excellent material compatibility with the aluminum base materials. However, there are some limitations of the Al-Si filler metals in a controlled atmosphere aluminum brazing process. For example, it is critical to have very precise control of the brazing temperature due to the small difference between the melting temperatures of the filler and base metals; and, the choices of the base metals are limited to certain alloys such as the 3xxx due to the material compatibility issues. Therefore, an aluminum brazing process that can be accomplished at a lower temperature and accommodate more alloy options is desirable. In recent years, the application of Zn based filler metal for brazing aluminum are becoming more widely studied (Dai *et al.*, 2012). Zn-

Al alloy is the type of filler metal that can offer a relatively low brazing temperature range ($<550^{\circ}\text{C}$). The development of Cesium Fluoroaluminate “non-corrosive” flux for assisting brazing aluminum with Zn-Al filler metals brings potential opportunities to heat exchanger manufacturing. In this paper, a series of experimental studies are performed to evaluate and compare the characteristics of Zn-Al filler metal and Al-Si filler metal in terms of wetting behavior on various aluminum alloys commonly used for heat exchangers. The brazing experiments of joining header materials and the extruded microchannel tube are performed to explore the feasibility of the low-temperature aluminum brazing process.

2. MATERIALS AND EXPERIMENTS

2.1 Materials for Brazing Tests

Two types of filler metals are used for the wetting test: (1) AA4047 alloy (Al-12wt%Si) that has a melting temperature of 577°C . (2) the Zn-15wt%Al alloy which has a relatively low melting temperature range ($382 - 452^{\circ}\text{C}$). Wetting tests are performed in a nitrogen atmosphere. The Nocolok® (a registered trademark of Solvay Fluor GmbH, Hannover, Germany) flux or Nocolok® Cs flux is used for the AA4047 wetting tests depending on the base alloy compositions; For Zn-Al filler metal, the cesium fluoroaluminate flux is used to assist wetting. All fluxes for wetting tests are manufactured by Solvay Fluor GmbH, Germany. Because of the non-corrosive nature of the flux residue at normal heat exchanger operating conditions and environment, the flux residues are not removed after brazing (Solvay Fluor document, 2013).

Brazing tests are performed to joining the header plate and microchannel tube samples. The dimension of a header sheet plate is around $100\text{mm} \times 50\text{mm} \times 1.5\text{mm}$. Two narrow slots for inserting microchannel tubes are fabricated on each plate. The microchannel (MC) tube is made of 3xxx series alloy. Two kinds of header plate, filler metal, and flux combinations are involved in the brazing tests: (1) the clad brazing sheet (AA4045/AA3003/AA4045) and the regular Nocolok® flux; (2) the unclad AA3003 header plate and the Zn22Al filler metal in a channel shape filled with flux (The ChannelFlux® rod manufactured by Bellman-Melcor, a Prince&Izant company).

2.2 Test Facilities

The wetting tests are performed using a transparent laboratory furnace. The samples are heated by the top and bottom electric heaters through radiation. The peak temperature at a base metal surface (measured by a thermocouple attached to the metal surface exposed to nitrogen gas) is controlled at around 580°C for the AA4047 alloy tests and around 450°C for the ZnAl alloy tests. The wetting behavior of the molten filler metals is observed in-situ through the transparent furnace wall during brazing. The heating chamber is purged with high purity nitrogen gas to provide a controlled atmosphere.

A batch type lab furnace is used for brazing tests of header plate and microchannel tubes. A controlled atmosphere aluminum brazing cycle with a peak brazing temperature around 610°C is applied to the sample using the AA4045 clad filler metal. A brazing cycle at a lower temperature around 525°C is applied to the sample using the ZnAl filler metal. Continuous nitrogen flow is provided as a protective atmosphere.

Part of the brazed header plate/MC tube samples are exposed to a cyclic salt fog spray corrosion test for a preliminary evaluation of the brazed joint corrosion resistance. The corrosion test is performed using a laboratory corrosion chamber for a 4-day duration. The test procedure follows the ASTM G-85 standard.

3. RESULTS AND DISCUSSION

3.1 wetting behavior of the filler metals.

Al12Si and Zn15Al filler metals for wetting tests are cut from wires (1.5mm in diameter). Each piece is approximately 2mm long. The actual volume of each filler metal piece may vary due to the manual cutting process. Two types of aluminum alloy base metals, AA3003 and AA6061, are prepared in the form of thin coupons (approximately $20\text{mm} \times 20\text{mm}$). These alloys are commonly used materials in HVAC&R heat exchangers. The major composition difference in these alloys is the Mg content. The nominal Mg concentration in AA3003 and AA6061 are 0 and 1.0wt%, respectively. Flux is applied in each sample. The flux melts before the filler metal and effectively removes the oxide layer to ensure good wetting of liquid filler metal on the aluminum surfaces. The specific combinations of materials are listed in Table 1.

A series of images extracted from the wetting test video of AA4047 (Al12Si) filler metal on the AA3003 surface is illustrated in Figures.1(a)-(c). This example illustrates the excellent wettability, i.e., very small contact angle, of AlSi filler metal on the AA3003 surface in the CAB brazing conditions. Another example of the extracted images of the Zn15Al filler metal on the AA3003 surface is presented in Figures.2(a)-(c). It is found that the Zn15Al filler metal has good wettability on the AA3003 surface, the contact angle is smaller than 90°. But the wetting is less extensive than the AlSi filler metal.

Table 1 Wetting test materials

Base plate	Filler metal	Flux
AA3003	Al12Si	Nocolok®
	Zn15Al	Cesium Fluoroaluminate
AA6061	Al12Si	Nocolok® Cs
	Zn15Al	Cesium Fluoroaluminate

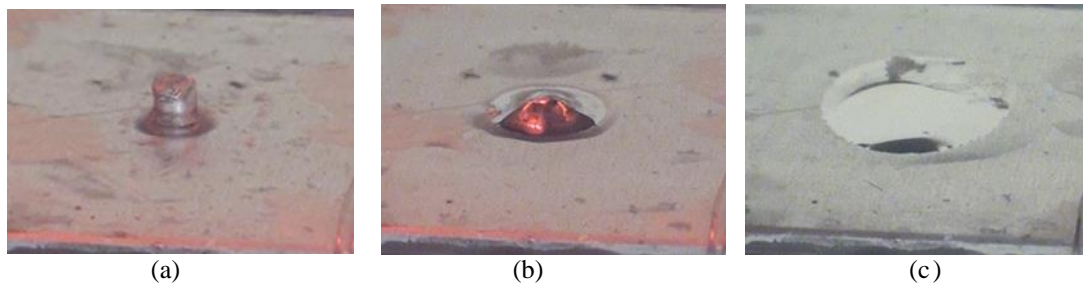


Figure 1: Sessile drop wetting test show excellent wettability of Al12Si filler metal on AA3003 surface : (a) Filler metal upon melting; (b) filler metal melting and spreading; (c) extensive wetting of liquid filler metal as temperature increases

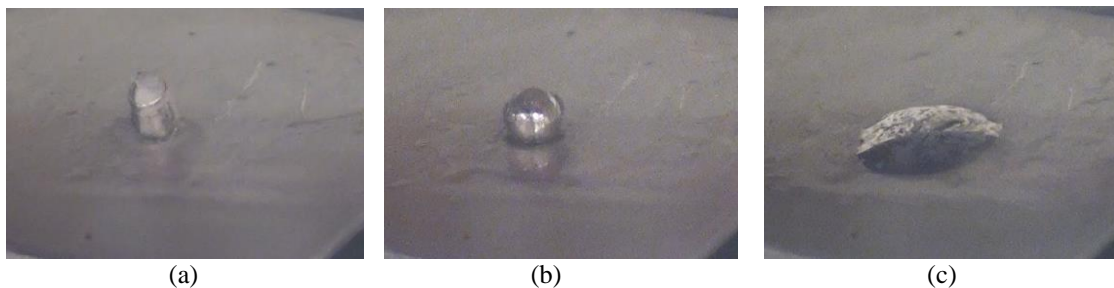


Figure 2: Sessile drop wetting test shows good wettability of ZnAl filler metal on AA3003 surface : (a) Filler metal upon melting; (b) filler metal melting; (c) good wetting of liquid filler metal as temperature increases.

The wettability of filler metal on the substrate surface is one of the key factors to ensure a successful brazing process. By performing the sessile drop wetting test, the wettability can be evaluated by measuring parameters such as the contact angle, wetting area and triple line movement of the filler metal drop. Traditional metallurgical analysis can be used to obtain a cross-section of the sample and measure the contact angle and triple line distance at a plane across the centerline of the droplet. Such a method relies on precise control of the cutting and polishing process. The information collected at one cross-sectional location may provide valuable information if the geometry of the resolidified sessile drop is relatively isotropic. However, for a sample that shows anisotropic geometric characteristics, the cross-section examination method by the destructive metallurgical process provides very limited and sometimes misleading information. In this study, a nondestructive inspection method is used to collect 3D geometrical information of the sessile drop samples to quantitatively evaluate the wetting performance of different filler metal and substrate combinations. The resolidified samples are scanned by a 3D laser scanning confocal

microscope (Keyence Corp. of America). The 3D imaging scanning results for the four test samples (see Table 1) are illustrated in Figure.3.

Figures 3(a)-(d) illustrate the 3D images of the wetting test of Al12Si and Zn15Al filler metals on AA3003, and AA6061 plates, respectively. The gray-scale image shows the view from the top, and the colored image shows a 3D view of the drops tilted at the same angle. The color map represents the height of the sessile drop surface at different locations. Figure 3(a) shows that the Al12Si filler metal has excellent wettability on the AA3003 surface. The filler metal covered area is much larger than in the other samples and the area shape is irregular. The triple line boundary is not well defined. As the substrate material change to magnesium(Mg) containing alloy AA6061(Figure.3(c)), the sessile drop shape becomes more circular, and the wetting contact angle is larger due to the Mg content in the substrated. In the case of Zn15Al filler metal, the wetting contact angle seems to increase as the Mg content increases in the aluminum substrate alloy, as illustrated in Figures.3(b) and (d). But the difference in wettability from sample to sample is not as significant as the samples using Al12Si as filler metals.

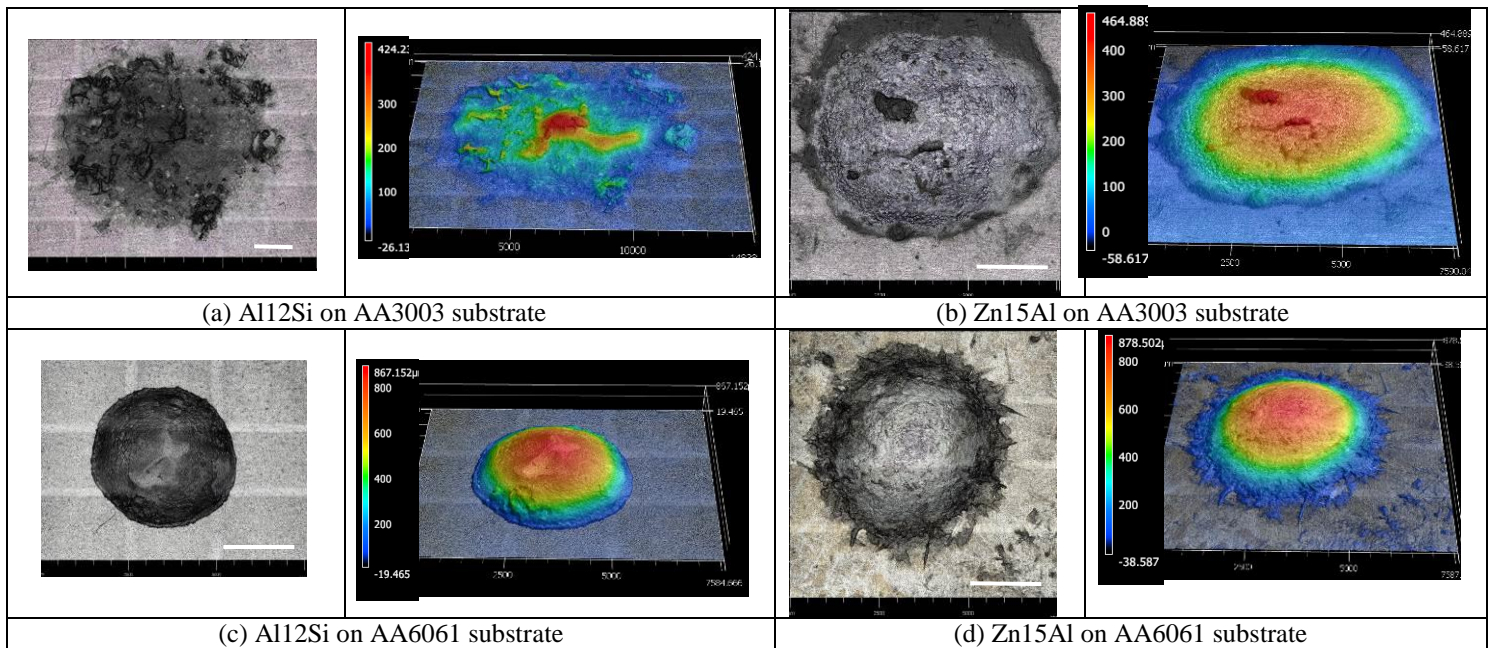


Figure 3: The scanned images provide the 3D view of the solidified filler metal surfaces after the wetting tests: the areas on the substrate covered by the filler metal are close to circular or elliptical shape except for the (a) AlSi on AA3003 plate, which has an extensive spreading area.

The 3D scanned data are acquired using the Kenyence MltiFileAnalyzer software. The 2D cross-section profiles can be extracted at specific locations for further analysis. In this study, two cross-sectional slices at the droplet center location perpendicular to each other are extracted. Due to the non-circular shapes of the wetting area, the center location of the droplet is approximated as the midpoint between the droplet edges as illustrated in Figure.4¹.

Such a profile extracting procedure was applied to all the wetting test samples. The surface profiles of Al12Si filler metal on different aluminum alloys are presented in Figure.5. These profiles can provide quantitative measurement of the spreading distance and contact angle of the filler metal at the specific cross-section. It can be seen that the profiles at the two perpendicular directions vary for the same droplet as a result of anisotropic geometry characters. However, the profiles at both directions show the same trends for the samples, i.e., the contact angle increases as the Mg content in substrate alloy increases. Wetting of the AlSi filler metal on the non-Mg-bearing AA3003 alloy is

¹ The surface profiles in Figures.4-6 are not presented in absolute scale, i.e., the scale ratio between Z over X(or Y) is large than 1 for illustration purpose.

significantly better than on the Mg-bearing AA6061 alloys. Therefore the 3xxx series alloy is preferred in the CAB process of manufacturing aluminum MCHXs.

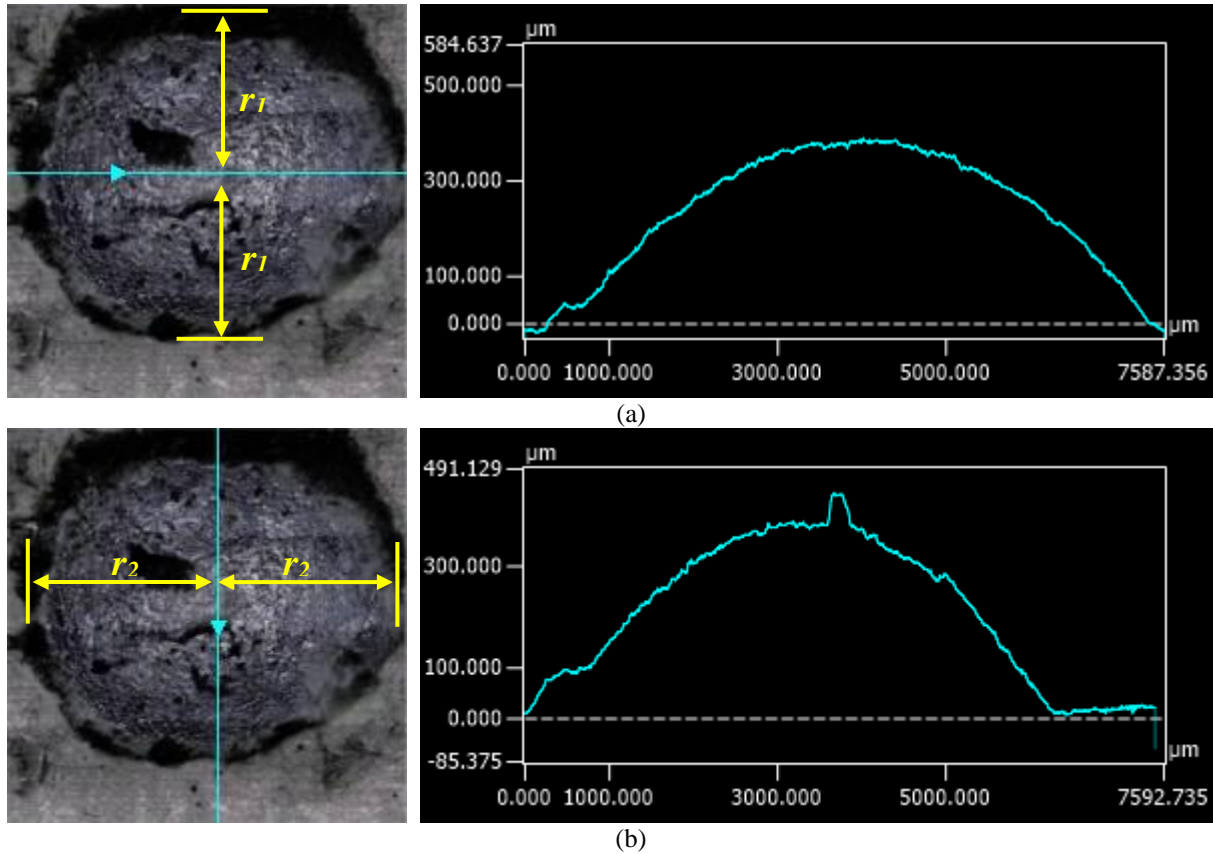


Figure 4: An example of extracting the sessile drop (ZnAl on AA3003) cross-section profiles at approximate center locations: (a) surface profile at the horizontal centerline; (b) surface profile at the vertical centerline.

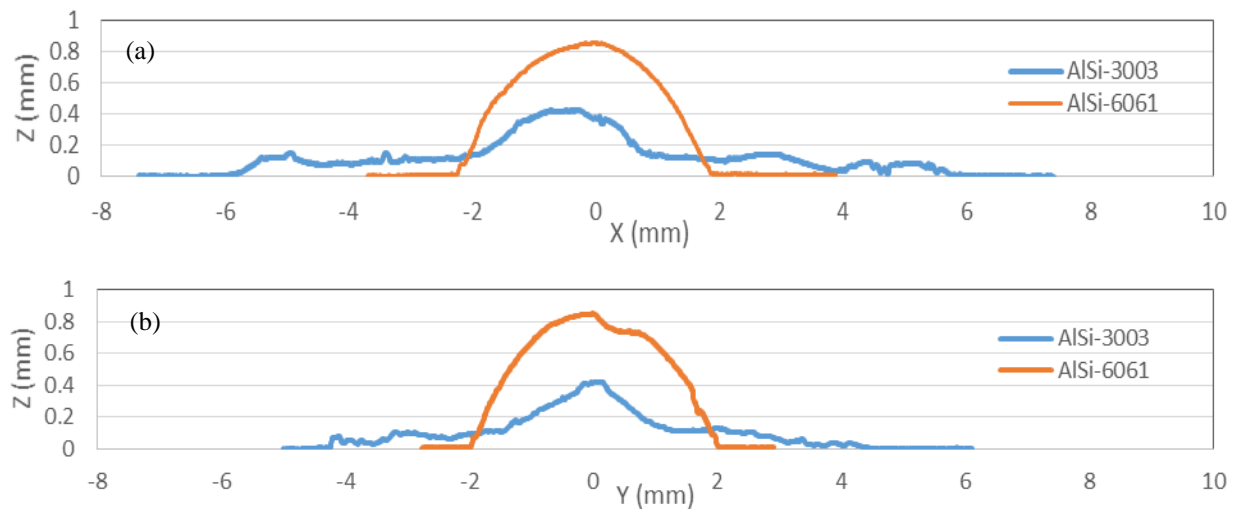


Figure 5: Comparison of the cross-section profiles of the resolidified Al12Si filler metal on different aluminum alloy plate shows better wetting in non-Mg-bearing substrate alloy: (a) surface profiles at the horizontal centerline; (b) surface profiles at the vertical centerline.

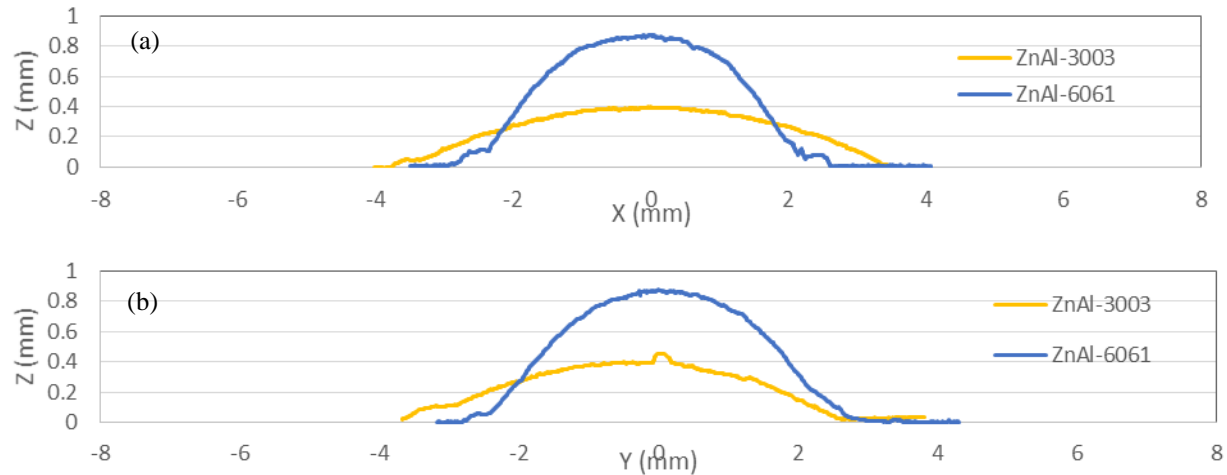


Figure 6: Comparison of the cross-section profiles of the resolidified Zn15Al filler metal on different aluminum alloy plates also shows better wetting for the substrate alloy without Mg, but the difference is not as significant as the AlSi filler metal. (a) surface profiles at the horizontal centerline; (b) surface profiles at the vertical centerline.

The extracted surface profiles of the Zn15Al sessile drops are presented in Figure.6. It is found that the geometric characters of these droplets are more isotropic. The profiles at different cross-sectional planes are fairly close to each other. There is also a trend in the samples that the wetting is improved when there is no Mg content in the substrate alloy. However, the difference is not as large as the wetting behaviors of the AlSi filler metal on different alloy base metals. The wetting of ZnAl filler metal on the AA3003 alloy is less extensive than the AlSi filler metal on the same substrate.

It should be mentioned that although the 3D scanning technology offers an easy and non-destructive way to evaluate the wetting performance of the filler metals on the substrate surface, there is also a disadvantage on the measurement accuracy, especially in the CAB brazed samples where the flux residue are always present on the sample surface. An in-depth analysis of how the flux load can affect the filler metal wetting behavior and wetting property measurement results using the 3D scanning technology will be further investigated.

3.2 Microstructure of the brazed joints

In addition to the wetting tests, brazing tests between header plates and MC tubes are performed. Two brazed samples with AlSi filler metal and ZnAl filler metal are presented in Figure.7(a) and (b), respectively.



Figure 7: Good joint integrity is observed in header plate/MC tube samples: (a) brazed with AA4045 filler metal; (b) brazed with ZnAl filler metal.

The materials used in these samples are described in 2.1. Visual inspection shows good joint integrity in both samples. After brazing, each sample is cut in half. One-half of the MC tube/plate sample is used for a 4-day cyclic salt fog spray test in a laboratory corrosion chamber. The joint samples at the as-is condition and corrosion tested conditions went through a series of metallurgical cutting, epoxy mounting and polishing processes for microscopic

analysis. The microscope images of the AlSi and ZnAl brazed joints at randomly selected locations are presented in Figure.8 and Figure.9, respectively.

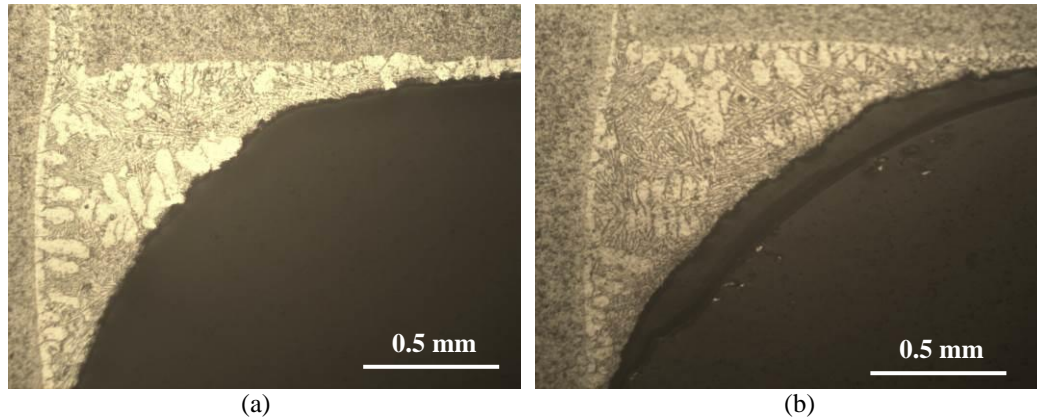


Figure 8: Examples of the AlSi (AA4045) brazed joints (a) without corrosion test; (b) after corrosion tests, show no apparent difference in the joint integrity

Good wetting of the AlSi filler metal (AA4045) on the AA3003 substrate is observed in the header plate and MC tube sample, see Figure. 8(a). After the 4-day corrosion test, the brazed joints using the AlSi filler metal show no significant change in the joint integrity as illustrated in Figure.8(b). The general good corrosion resistance of the aluminum joint brazed with the AlSi filler metal is confirmed in this short term laboratory corrosion test.

The brazed joints using the ZnAl filler metal at a lower temperature around 525°C also show good joint integrity as illustrated in Figure.9(a). However, after the 4-day corrosion test, apparent surface pitting most likely due to corrosion is observed, see Figure. 9(b). It is generally understood that the ZnAl brazed joint has inferior corrosion resistance to the AlSi filler metal (Zhang and Zhuang, 2017). The application of the ZnAl filler metal in aluminum heat exchangers should be considered in a mild operating environment. The fact that the ZnAl filler metal requires a much lower brazing temperature may also offer potential opportunities in heat exchanger repair (Zhao *et al.*, 2018).

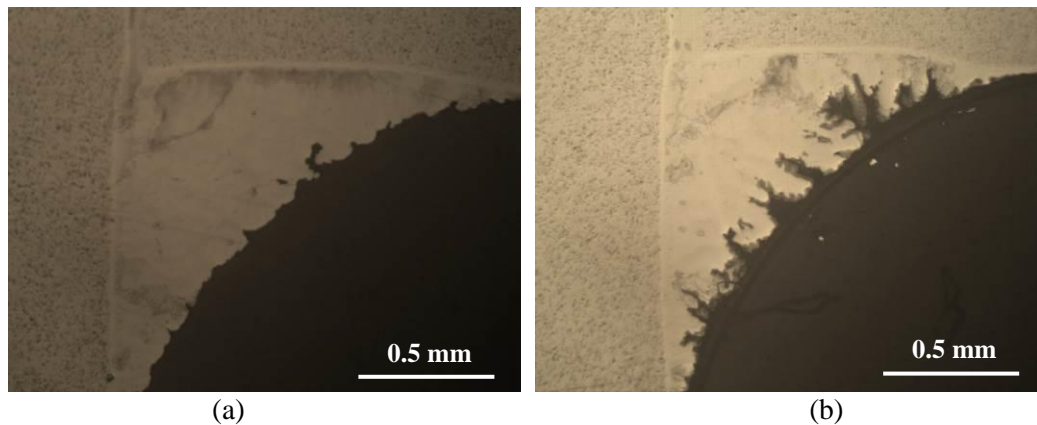


Figure 9: Examples of the ZnAl brazed joints (a) without corrosion test; (b) after the corrosion test where apparent joint damage due to corrosion has been observed.

4. CONCLUSIONS

In this study, the wetting behaviors of the ZnAl filler metal on various aluminum alloys are compared with the AlSi filler metal. Brazing experiments on small scale header plate/MC tube samples are performed using both AlSi and ZnAl filler metal. The brazed samples are exposed to short term laboratory corrosion test to evaluate the brazed joint corrosion resistance. The preliminary experimental results are summarized as follows:

- Under the CAB brazing conditions, Al12Si filler metal shows superior wettability on the AA3003 base metal.
- ZnAl filler metal requires a much low brazing temperature than the AlSi filler metal. Zn15Al filler metal shows good wettability on the AA3003 base metal, i.e., the wetting contact angle is smaller than 90°. However, the wettability is inferior to the AlSi filler metal on the AA3003 surface.
- For both Al12Si filler metal and ZnAl filler metal, the wettability decreases as the Mg content in the base metals, such as AA6061, increases.
- The header plate and MC tube brazed joints by AlSi filler metal and ZnAl filler metal both show good filler metal wettability and joint integrity. However, the preliminary corrosion test shows worse corrosion resistance of the ZnAl brazed joints compared to the AlSi brazed joints.

REFERENCES

American Society for Testing and Materials, 2011, *Standard Practice for Modified Salt Spray (Fog) Testing* (ASTM G85-11).

Dai, W., Xue, S.B., Lou, J.Y., Lou, Y.B. and Wang, S.Q., 2012, Torch brazing 3003 aluminum alloy with ZnAl filler metal, *Trans. Nonferrous Met. Soc. China*, Vol 22, pp30-35.

Solvay Fluro document, 2013, Nocolok encyclopedia, available online at <https://www.aluminium-brazing.com/sponsor/nocolok/Files/PDFs/NOCOLOK-Encyclopedia-2013.pdf> (accessed January, 2021)

Zhang, Q.Y. and Zhuang, H.S. 2017, *Handbook of Brazing and Soldering*, 3rd edition, China Machine Press. (in Chinese).

Zhao, H., Elbel, S. and Hrnjak, P., 2018, Compatibility of filler and base materials in heat exchanger manufacturing process. 17th International Refrigeration and Air Conditioning Conference at Purdue, July 9-12, 2018, West Lafayette, Indiana.

ACKNOWLEDGEMENT

The surface profile scan imaging was performed in the Frederick Seitz Materials Research Laboratory Central Research Facilities, University of Illinois.